

# Investigation of Wire Lengths in Advanced LIGO Quadruple Pendulum Design for ETM/ITM

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## 1. Introduction.

An updated conceptual design for the quad pendulum suspension for the test masses in Advanced LIGO has been presented in the document “Advanced LIGO Suspension System Conceptual Design”, T010103-03-D, 21 October 2003. Since that design was first put together, we have been considering alternative parameter sets for various reasons. In this document I address the overall length of the pendulum and in particular the individual lengths of the first and third stages (counting from the top).

The general design which has been developed is such that either a sapphire or a silica test mass of the same mass could be suspended – see NAR’s talk at the LSC meeting in Hannover, Aug 2003: "Quadruple Pendulum Design Update" G030437-00-Z (not yet posted on the LSC website). However for the purposes of this document, I have assumed that sapphire is the material used for the test mass, and that the penultimate mass has the same mass and density as sapphire.

## 2. Changes to wire lengths in quad pendulum.

### 2.1 Increasing space for catcher

The lengths of the wires quoted in the conceptual design, from top to bottom, were 0.54, 0.304, 0.302, 0.6 m. Note that the wires in the first three stages are not vertical, and that the attachments are not exactly at the centres of mass – so the overall length from top blade to centre of optic is not simply the sum of these values. The full calculation is done in the MATLAB program. The first change which was made to these lengths was to increase the length between the 2<sup>nd</sup> (upper intermediate) and 3<sup>rd</sup> (penultimate) masses by ~4 cm to allow more room for fitting in the “catcher” structure which will be used for the assembly and installation of the penultimate and test mass. i.e. wire lengths become 0.54, 0.304, 0.342, 0.6 m. With this revised length, and holding all other parameters as given in the conceptual design, the overall vertical length of the pendulum from the tip of the top blades to the base of the optic becomes 1.894 m, and allowing for 0.211 m divided above and below the pendulum for the overall supporting structure which attaches to the optical table, leads to an overall vertical length including structure of **2.105 m**. These numbers are captured in the document “ETM Controls Prototype: - Mass estimate of an ETM suspension layout”, T030137-04, written to allow mass budget and centre of mass to be estimated for use by the SEI subsystem. Note: in that document, due to rounding errors,

the overall length is quoted as 1.893 m and the lengths allowed above and below total 0.212 m to give the overall vertical length of 2.105 m.

## 2.2 Shortening overall length for ease of installation.

The overall vertical length including support structure is in general constrained by several factors: the height of the crane above the tanks, the size of the SEI structure, the method of installing both SEI and SUS into the tank, the position of the SEI structure within the tank and the height of the optical beam. The prime consideration for the quad is to come up with an acceptable length which meets performance requirements and can be installed in LIGO. A secondary consideration is installation at LASTI. We are currently planning to install the SEI and SUS in LIGO as a single unit, with the intention that the quad will be built so that it can be split into an upper and lower section, the lower section comprising the catcher structure containing the penultimate and test masses. With such a split structure, we would have the facility of removing and replacing the lower part without removal of the SEI and upper part of the SUS, if and when required.

The SUS team has been asked to consider whether we could reduce the overall length to 2.005 m to allow LASTI installation without major structural changes at the facility. There are two issues with installing the quad pendulum structure at LASTI due to restricted headroom. See document D030715-00-D (L Jones). The first issue arises due to the required addition of a spreader beam to allow connection of two cranes to a single lift pin on the top of the SEI. With the additional height this implies we will *require* the quad to be installed in two pieces whatever its length. The second problem arises with putting the dome in place once the SEI and SUS are installed. The dome will not clear the top of the SEI structure if a 2.105 m SUS is in place and the optics is hanging at the correct height for the optical beam, unless it is split into two pieces. However the dome can be installed if the SUS structure is 10 cm shorter. (Note: there is potentially another fallback position – the optical beam height could be changed.). If the quad could be 10 cm shorter this would be the simplest solution for LASTI installation.

We believe that the ~0.2 m total added to the basic quad pendulum length for the supporting structure is close to the minimum we can use to allow for clamps, catcher, etc. Thus we have considered taking 10 cm off the quad itself. Noting the wire lengths as given above, and recalling that the lowest length (0.6 m), corresponding to the silica ribbons/fibres, has been carefully chosen from thermal noise considerations, the obvious place to consider removal of 10 cm is in the top length. Thus we have run the MATLAB model with wire lengths 0.445, 0.304, 0.342, 0.6 m, other parameters remaining unchanged, to give an overall vertical length from tip of top blades to base of optic of 1.793 m. (slightly less than 10 cm being taken off the top wire length, which is at a small angle to the vertical, to give 10 cm off the vertical length).

### 2.3 Results of changes to wire lengths.

We will look at the effect of doing both the changes outlined in 2.1 and 2.2 taken together. We consider mode frequencies, transfer functions for seismic and sensor noise and impulse decay times. Since the thermal noise behaviour is dominated by the final stage (unchanged) at frequencies around and above 10 Hz, we do not reconsider this here.

The MATLAB model used for these investigations is available as QUAD\_2003NOV14. The full parameter set is given in Appendix A.

The frequencies of the modes for the two sets of wire lengths are given in Table 1.

longpitch1: [0.372 0.433 0.867 0.960]
longpitch2: [1.98 2.00 3.41 4.16]
yaw: [0.646 1.37 2.39 3.14]
transroll1: [0.441 0.820 0.976 2.03]
transroll2: [2.73 3.56 3.93 12.5]
vertical: [0.687 2.73 4.40 8.76]

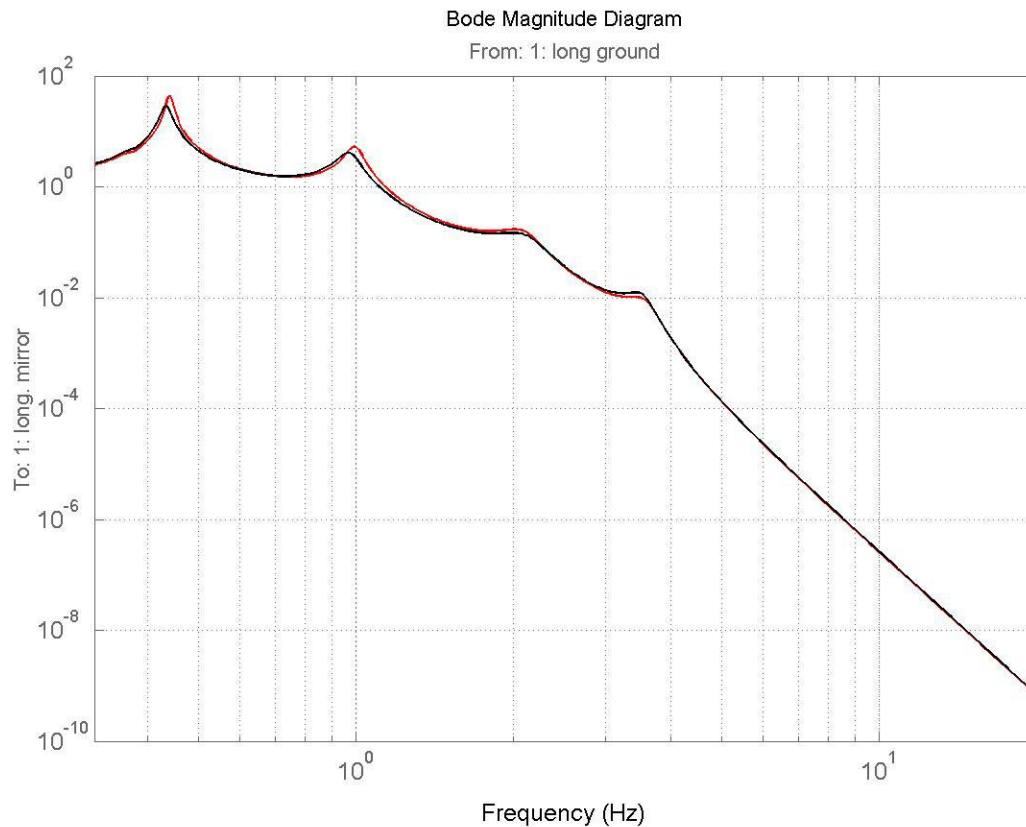
longpitch1: [0.370 0.440 0.867 0.987]
longpitch2: [1.92 1.99 3.42 4.10]
yaw: [0.666 1.40 2.42 3.07]
transroll1: [0.447 0.841 1.00 2.02]
transroll2: [2.78 3.56 3.96 12.5]
vertical: [0.686 2.73 4.40 8.76]

*Table 1. Mode frequencies in Hz for two sets of wire lengths: upper set 0.54, 0.304, 0.302, 0.6 m, lower set 0.445, 0.304, 0.342, 0.6 m, as given by MATLAB model.*

One can see that the changes are very small as expected. The lowest longitudinal mode at around 0.44 Hz is slightly higher due to the slightly shorter overall length, but the change is less than 2% and similarly other changes are of this magnitude. These frequencies were also checked using M Barton's Mathematica program which more accurately models the effect of non-vertical wires attached to the tips of the blades. The frequencies in general agree well to those given in Table 1, and again show changes between the different wire lengths only at the few or less percent level. We should point out here one frequency – the second highest transroll mode, is not well modeled with the MATLAB code at present. This mode corresponds to the movement of the two top masses in antiphase in roll and for this mode the non-vertical wire/blade interaction does play a significant role. The Mathematica program shows that this mode is in fact around 5.5 Hz for both sets of wire lengths, compared to the value of  $\sim 4$  Hz which the MATLAB model predicts. A full listing of the modes predicted using the Mathematica code is given in Appendix B.

Checking on vertical and longitudinal transfer functions, we find that the vertical TFs are essentially unchanged. With the same local control gain, the longitudinal TF shows that the first and second modes are slightly less damped with the new lengths, see Figure 1.

Looking at the impulse response this is more clearly seen – for a gain which gives a decay time of 10.0 s with the old lengths, the decay time rises to 15.4 secs for the new



*Figure 1: longitudinal transfer functions: black curve – wire lengths as in conceptual design, red curve – new lengths.*

lengths. See figure 2. This (and a similar change in the transverse direction) is the only significant change to any of the transfer functions. Increasing the gain to give a decay time of 10 s slightly raises the value of the TF at 10 Hz, but at a value of  $\sim 3.4 \times 10^{-7}$ , this, combined with the level of residual noise specified at the optics table of the active platform, will meet the overall longitudinal noise requirement.

### 3 Conclusions.

Introducing the length changes discussed above, resulting in an overall structure height of 2.005 m for the ETM, looks acceptable. This allows for a LASTI installation without major facility changes. It is thus recommended that these new wire lengths should be adopted as the working design.

It is worth pointing out here that in LIGO itself the various BSC suspension optics do not lie at the same heights in the different tanks due to changes in height of the optical beam. In particular if one defines the beam hitting the ETMs as lying at zero, the beam at ITMy

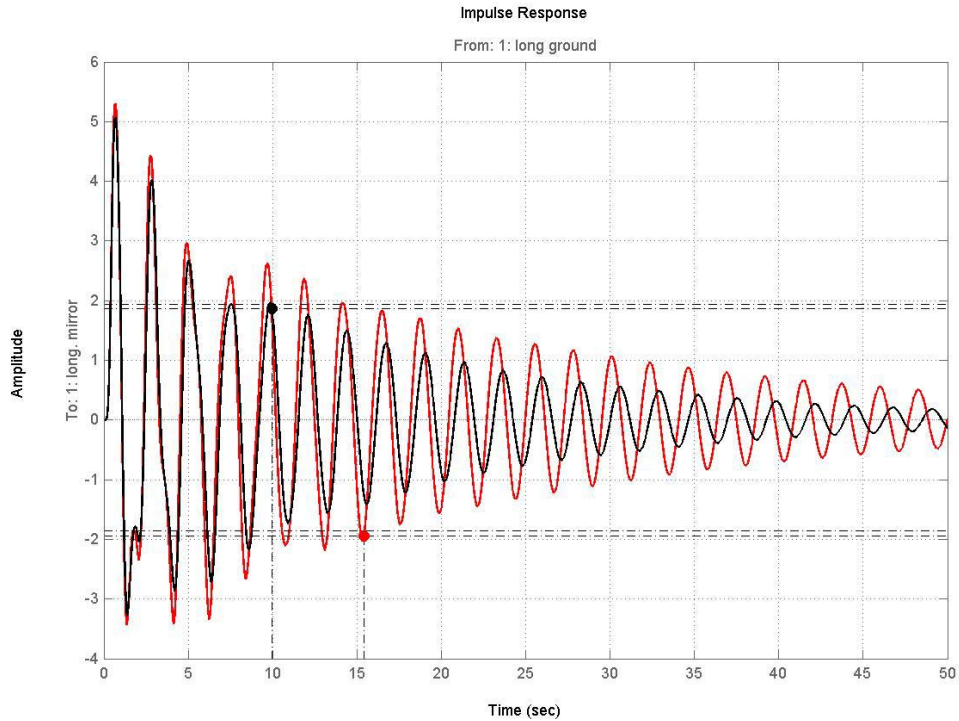


Figure 2: longitudinal impulse response: black curve – wire lengths as in conceptual design, red curve – new lengths. Dots on curves represent decay time to  $1/e$ .

lies 8 mm below zero and the beam at the beamsplitter lies 70 mm below zero. For these suspensions, extra spacers would be required between the optical table and the structure if the same length of pendulum and structure is used or potentially, in particular for the beamsplitter, a longer pendulum and associated structure could be used.

## 5 Appendix A

List of parameters.

pend =

g: 9.8100  
 nx: 0.1300  
 ny: 0.5000  
 nz: 0.0840  
 denn: 4000  
 mn: 21.8400  
 Inx: 0.4678  
 Iny: 0.0436

Inz: 0.4858  
ux: 0.1300  
uy: 0.5000  
uz: 0.0840  
den1: 4000  
m1: 21.8400  
I1x: 0.4678  
I1y: 0.0436  
I1z: 0.4858  
ix: 0.1300  
ir: 0.1570  
den2: 3980  
m2: 40.0660  
I2x: 0.4938  
I2y: 0.3033  
I2z: 0.3033  
tx: 0.1300  
tr: 0.1570  
den3: 3980  
m3: 40.0660  
I3x: 0.4938  
I3y: 0.3033  
I3z: 0.3033  
ln: 0.4450 \* varied in section 2  
l1: 0.3040  
l2: 0.3420 \* varied in section 2  
l3: 0.6000  
nwn: 2  
nw1: 4  
nw2: 4  
nw3: 4  
rn: 7.0000e-004  
r1: 4.0000e-004  
r2: 3.5000e-004  
r3: 2.0000e-004  
Yn: 2.2000e+011  
Y1: 2.2000e+011  
Y2: 2.2000e+011  
Y3: 7.0000e+010  
lnb: 0.4800  
anb: 0.0961  
hnb: 0.0045  
ufcn: 2.3628  
stn: 8.9866e+008  
intmode\_n: 73.5303  
l1b: 0.4200

a1b: 0.0583  
h1b: 0.0049  
ufc1: 2.5555  
st1: 8.9994e+008  
intmode\_1: 104.5764  
l2b: 0.3400  
a2b: 0.0500  
h2b: 0.0045  
ufc2: 2.1106  
st2: 7.9192e+008  
intmode\_2: 146.5517  
dm: 0.0010  
dn: 0.0010  
d0: 0.0010  
d1: 0.0010  
d2: 0.0010  
d3: 0.0010  
d4: 0.0010  
twistlength: 0  
d3tr: 0.0010  
d4tr: 0.0010  
sn: 0  
su: 0.0030  
si: 0.0030  
sl: 0.0200  
nn0: 0.2500  
nn1: 0.0900  
n0: 0.2000  
n1: 0.0700  
n2: 0.1200  
n3: 0.1635  
n4: 0.1585  
n5: 0.1585  
tln: 0.4162  
tl1: 0.2768  
tl2: 0.3412  
tl3: 0.6020  
l\_suspoint\_to\_centreofoptic: 1.6363  
l\_suspoint\_to\_bottomofoptic: 1.7933

Appendix B. Comparison of MATLAB and Mathematica mode frequency predictions for the various parameter sets considered in this document.

MATLAB

Mathematica

Conceptual design parameters  
*(Wire lengths 0.54, 0.304, 0.302, 0.6 m)*

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longpitch1: [0.372 0.433 0.867 0.960]  
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 transroll1: [0.441 0.820 0.976 2.03]  
 transroll2: [2.73 3.56 3.93 12.5]  
 vertical: [0.687 2.73 4.40 8.76]

longpitch1 0.368 0.433 0.862 0.960  
 longpitch2 1.96 2.00 3.41 4.14  
 yaw 0.650 1.37 2.40 3.17  
 transroll1 0.459 0.878 1.01 2.08  
 transroll2 2.73 3.51 5.47 12.5  
 vert 0.703 2.77 4.51 8.76

*Wire lengths 0.445, 0.304, 0.342, 0.6 m*

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longpitch1: [0.370 0.440 0.867 0.987]  
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 vertical: [0.686 2.73 4.40 8.76]

longpitch1 0.366 0.440 0.862 0.987  
 longpitch2 1.90 1.99 3.42 4.08  
 yaw 0.671 1.40 2.43 3.10  
 transroll1 0.466 0.882 1.05 2.12  
 transroll2 2.79 3.50 5.53 12.5  
 vert 0.703 2.77 4.51 8.76